REMARKS/ARGUMENTS

Before discussing the substance of the present application, it should be noted that this amendment accompanies the second Request for Continued Examination (RCE) filed in the present application. Accordingly, **should the Examiner consider any of the claims not in condition for allowance upon review of the present amendment, the undersigned requests the Examiner to contact him at (425) 455-5575 to arrange for a telephone interview to discuss the outstanding issues**.

Claims 2-6, 8-11, 14, 15, 22, 24-33, and 41-44, and 46-49 are currently pending in the present patent application, with claims 1, 19-21, and 45 having been cancelled through the above claim amendments and the remaining ones of the claims having been withdrawn. These amendments introduce no new matter into the application.

In a final Office Action mailed 20 July 2006 and during an interview conducted with the Examiner on 22 September 2006, the Examiner has maintained his rejections of the currently pending claims as being anticipated in view of U.S. Patent No. 5,807,789 to Chen *et al.* ("Chen") and various other cited references.

Claim 2 recites a process for forming trenches with an oblique profile and rounded top corners. The process includes, in part, controlling an etching voltage between a plasma around a semiconductor wafer and said wafer to form trenches with oblique profiles having a substantially constant slope throughout substantially an entire sidewall of each trench. This claim, along with several others, was discussed with the Examiner during the telephone interview. See, for example, paragraph 25 of the present application for it is explained that plasma etching is performed by placing the wafer 20 in an etching chamber 32 in which a known mixture of gases flows in predetermined conditions of temperature, pressure and flow. See Figure 16. In addition, the etching chamber 32 is set at a chamber voltage VC while the wafer 20 is kept at a wafer voltage VW. The plasma, coming into contact with the etching chamber 32, reaches a plasma voltage VP higher by a known amount than the chamber voltage VC. An etching voltage VE =VP-VW is present between the exposed surface of the wafer 20 (more specifically, of the substrate 21) and the plasma. This etching voltage VE is controllable through the wafer voltage VW and the rate of removal of the silicon and the rate of microdeposition of the polymeric material of the

plasma are a function of the etching voltage VE. In particular, all other conditions being equal, the rate of microdeposition increases as the absolute value of the etching voltage VE increases.

In rejecting claim 2, the Examiner points to the two etching processes discussed in column 3 of Chen, namely the first etching process that is discussed starting in-line 14 of column 3 and the second etching process that is discussed starting in line 29 of this column. The Examiner asserts that by applying two different RF powers to the plasma the "etching voltage" between the wafer and the plasma is being varied.

Four objective references accompany this amendment and evidence that the Examiner's position regarding the two different RF powers in Chen varying the etching voltage is incorrect. These four references, designated A, B, C and D, are attached, with the bibliographic information for these references as follows:

1. Reference A: Hong Xiao, INTRODUCTION TO SEMICONDUCTOR MANUFACTURING TECHNOLOGY (Prentice-Hall, 2001);
2. Reference B: CY Chang, SM Sze, ULSI technology (McGraw Hill, 1996);
3. Reference C: FF Chen, JP Chang, Principles of Plasma Processing (UCLA, 2002); and
4. Reference D: http://www.lamrc.com/tech_1_1.cfm (hardcopy of this Web page is attached).

Referring first to Reference A, this reference discusses an inductively coupled plasma (ICP) source or system including inductive coils as shown in Figure 7.21(a) and (b). When an RF current flows in the coils, this current generates a changing magnetic field which, in turn, generates a changing electric field that accelerates electrons and causes ionization collisions (Figure 7.21(a)). As shown in Figure 7.21(b), the ICP system includes an RF source coupled to the inductive coils along with an RF bias coupled to the ICP chamber in which the plasma is generated. This RF bias is added to the ICP chamber to generate self-bias and control ion bombardment energy. In the ICP system, ion flux, which

is mainly determined by plasma density, is controlled by the power of the RF source while ion bombardment energy is controlled by the power of the RF bias. Paragraph 7.4.6 of Reference B similarly describes an ICP system including an RF source applied to a coil and an RF bias applied to the wafer. Reference C also describes that in an ICP system there "is no large RF potential in the plasma, so the wafer bias is not constrained to be high" and this "bias can be set to an arbitrary value with a separate oscillator, so the ion energy is well controlled." Reference D similarly states that in transformer coupled plasma (TCP) systems, where TCP is another name for an ICP system, source power is supplied by a simple planar coil located at the top of the etch chamber while a separate power supply delivers bias voltage to the lower electrode (wafer) to provide independent control of ion energy, which influences parameters such as selectivity and critical dimensions bias.

As discussed above, paragraph 25 of the present applications states that:

> The plasma, coming into contact with the etching chamber ***32***, reaches a plasma voltage V_P higher by a known amount than the chamber voltage V_C. Consequently, an etching voltage $V_E=V_P-V_W$ is present between the exposed surface of the wafer ***20*** (more specifically, of the substrate ***21***) and the plasma; in addition, the etching voltage V_E is controllable through the wafer voltage V_W.

Varying the RF power, as Chen discloses, does not vary and certainly does not correspond to controlling the etching voltage. The cited References A-D plainly illustrate the different voltages in an ICP system and demonstrate that varying the RF power source is not the same as varying the etching voltage. Neither is varying the RF power the same as controlling the etching voltage. Chen only refers to RF power, that is to power supplied to a gas mixture to create a plasma, which is the conventional and well understood meaning of RF power. Indeed, the RF power is necessary to bring the gas mixture into the plasma state and varying the RF power changes plasma conditions. The RF power does not, however, affect the etching voltage, which in turn determines the energy of ions leaving plasma to reach the wafer. As evidenced by References A-D, the etching voltage is a separate parameter in plasma etching systems to provide an independent control of ion energy of ions reaching the wafer. In addition, controlling the etching voltage modifies only ion energy and does not have any substantial impact on plasma stability, which is of

important to control. To the contrary, RF power changes cause transients and instability in the plasma that harm fine control of etching conditions.

It should be noted that when RF power is supplied and a plasma is created from a mixture of gases, a so called "sheath voltage" is set around the wafer, at the interface of the wafer and the plasma. This sheath voltage is affected by RF power to some extent. However, large RF power variations may only cause negligible variations of the sheath voltage between the plasma and the wafer. The sheath voltage and its variations are so small that they do not have any practical effect and are not even considered in plasma etch applications. In any event, possible minor variations in the etching voltage are not the intended result of varying RF power so one skilled in the art would not consider RF power as a control means to modify the plasma-to-wafer etching voltage and would not intend that the etching voltage is changed when RF power varies. The etching voltage is separately and independently controlled.

For these reasons, the combination of elements recited in independent claim 2 is allowable. Chen simply does not inherently disclose controlling the etching voltage as asserted by the Examiner. Dependent claims 3-6, 8-11, 14, and 15 are allowable for at least the same reasons as claim 2 and due to the additional limitations added by each of these claims.

Independent claim 24 recites, in part, a method that includes setting a chamber voltage, setting a series of substrate voltages, and creating a series of etching voltages between the substrate and the second plasma mixture of gases. As just described above, Chen does not disclose or suggest controlling the etching voltage but only varying the RF power. Accordingly, the combination of elements recited in claim 24 is allowable and dependent claims 22, 25-33, and 41-44 are allowable for at least the same reasons as claim 24 and due to the additional limitations added by each of these claims.

Independent claim 46 recites, in part, a method for forming trenches with an oblique profile and rounded top corners in a wafer that includes controlling an etching voltage between a plasma around the wafer and the wafer. The combination of elements recited in claim 46 is accordingly allowable. Depending claims 47-49 are allowable for at least the same reasons as claim 46 and due to the additional limitations added by each of these dependent claims.

Finally, it should be noted that in the present application the term "etching voltage" is clearly defined and consistently utilized. There is no ambiguity between what is meant by "controlling the etching voltage" recited in the present claims and what is occurring in the prior art systems, including Chen. As discussed above with reference to paragraph 25 of the present application, the etching voltage VE is controllable through the wafer voltage VW. This is plainly and unambiguously set forth in the present patent application. The term etching voltage is by definition related to and defined in part by the wafer voltage VW.

The present patent application is in condition for allowance. Favorable consideration and a Notice of Allowance are respectfully requested. As set forth above, should the Examiner consider any of the claims not in condition for allowance, the undersigned requests the Examiner to contact the undersigned attorney at (425) 455-5575 to arrange for a telephone interview to discuss the outstanding issues. If the need for any fee is found, for any reason or at any point during the prosecution of this application, kindly consider this a petition therefore and charge any necessary fees to Deposit Account 07-1897.

Respectfully submitted,

GRAYBEAL JACKSON HALEY LLP

Paul F. Rusyn
Registration No. 42,118
155 – 108th Avenue NE, Suite 350
Bellevue, WA 98004-5973
(425) 455-5575 Phone
(425) 455-5575 Fax

Enclosures:

- Petition to Revive (Unintentional)
- Request for Continued Examination
- Request for Extension of Time
- Check #27260 for $1,500.00
- Check #27264 for $1360.00
- Return postcard

A

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7.10 HIGH-DENSITY PLASMA

A plasma source that can generate high-density plasma at low pressu (~ a few mTorr) is highly desirable for both etch and CVD processes. F etch processes, lower pressure gives longer ion MFP, and less ion collision scattering, which enhances etch profile control. High-density plasma also pr vides more free radicals, which accelerate etching processes. For CV processes, high-density plasma can achieve excellent gap-fill capability by situ, simultaneous deposition/etchback/deposition processing.

A conventional, capacitively coupled plasma source cannot genera high-density plasma. In fact, it is very difficult to generate plasma even in magnetic field when the chamber pressure is only a few mTorr. At that lo pressure, the electron mean free path could be about the same or even long than the electrode spacing, so there are not enough ionization collision Therefore, different mechanisms are needed to generate high-density plasma at very low pressure.

Another drawback of capacitively coupled plasma sources is that both io flux and ion energy are directly related to RF power, therefore it cannot inde pendently control these two. To achieve better etch and CVD process contro as the feature size continuously shrinks, it is necessary for a plasma source t be able to independently control both ion flux and ion energy.

Two kinds of high-density plasma sources are most commonly used in th semiconductor industry: inductively coupled plasma, ICP (also called TCP, fo transformer-coupled plasma) source and electron cyclotron resonance, ECR plasma source. Both can generate high-density plasma at few mTorr with th ability to control the ion bombardment flux and energy independently.

7.10.1 Inductively Coupled Plasma (ICP)

The mechanism of an inductively coupled plasma source is similar to a trans former, which is why it is also called a transformer-coupled plasma (TCP source. The inductive coils shown in Figure 7.21 (b) serve just like the prima coils of a transformer. When an RF current flows in the coils, it generates a changing magnetic field, which in turn generates a changing electric field through inductive coupling, as shown in Figure 7.21 (a). The inductively cou pled electric field accelerates electrons and causes ionization collisions. Sinc the electric field is in the angular direction, electrons are accelerated in th angular direction, which allows electrons to travel a long distance without co lisions with the chamber wall or electrode. That is why an ICP system can gen erate high-density plasma at low pressure (a few mTorr).

1) Hong Xiao: Intro to semicond. manufacturing tech

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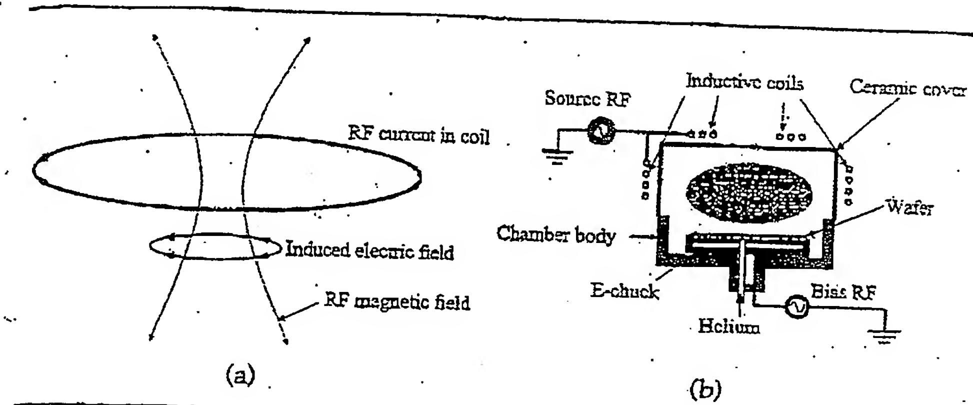
Figure 7.21
(a) Inductive coupling and (b) schematic of ICP chamber.



The ICP design is very popular in the semiconductor industry. Systems include high-density plasma (HDP) dielectric CVD systems; silicon, metal, and dielectric HDP etching systems; native oxide sputtering clean systems; and ionized metal plasma PVD systems.

A bias RF system is added to the ICP chamber to generate self-bias and control ion bombardment energy. Since ion bombardment from high-density plasma generates a lot of heat, a helium back-side cooling system with E-chuck is needed for better wafer temperature control. In the ICP system, ion flux, which is mainly determined by the plasma density, is controlled by the source RF power; ion bombardment energy is controlled by the bias RF power.

7.10.2 Electron Cyclotron Resonance (ECR)

Charged particles tend to rotate in a magnetic field. The frequency of the rotation, called *gyrofrequency* or *cyclotron frequency*, is determined by magnetic field strength. From section 7.4.4, electron gyrofrequency is equal to:

$$\Omega_e \text{ (MHz)} = 2.8B \text{ (Gauss)}$$

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B

2) Chang - Sze : ULSI Technology

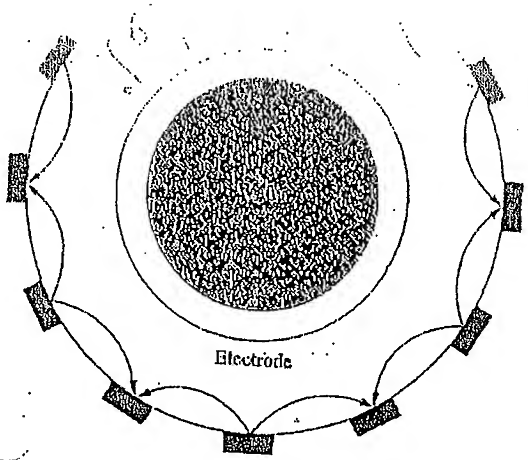

FIGURE 17
Schematic of magnetic-confinement reactive ion etch reactor with a multipolar magnetic bucket surrounding the reactor chamber.

7.4.5 Electron Cyclotron Resonance Plasma Etchers (ECR)

Most parallel-plate plasma etchers, except triode RIE, do not provide the ability to independently control plasma parameters, such as electron energy, ion energy, plasma density, and reactant density. As a result, ion-bombardment-induced damage becomes serious as device dimensions shrink.

ECR etching uses microwave excitation in the presence of a magnetic field to generate a high-density discharge. The Lorentz force causes the electrons to circulate around the magnetic field lines in circular orbits, with a characteristic cyclotron frequency of

$$\omega_{ce} = \frac{eB}{m_e} \tag{7.16}$$

where e is the electron charge, B is the magnetic field, and m_e is the electron mass. When this frequency equals the applied microwave frequency, a resonance coupling occ[urs] between the electron energy and the applied electric field, which results in a hi[gh] degree of dissociation and ionization (10^{-2} for ECR compared to 10^{-6} for RIE).[20] With a microwave frequency of 2.45 GHz, the required magnetic field is 875 gauss. Figure 18 shows one of the possible ECR plasma-etching configurations.[21] Microwave power is coupled via a waveguide through a dielectric window into the ECR source region. The magnetic field, supplied from magnetic coils, decreases as a function of distance from the coils.

Because the gradient in the magnetic field decreases, the electrons are accelerated away from the plasma source, creating a negative potential in the direction of the wafer. Ions diffuse by ambipolar diffusion out of the source region into the wafer process chamber. The wafer is rf- or dc-biased to control the energy of the ions to achieve the desired etch anisotropy. Plasma uniformity degrades

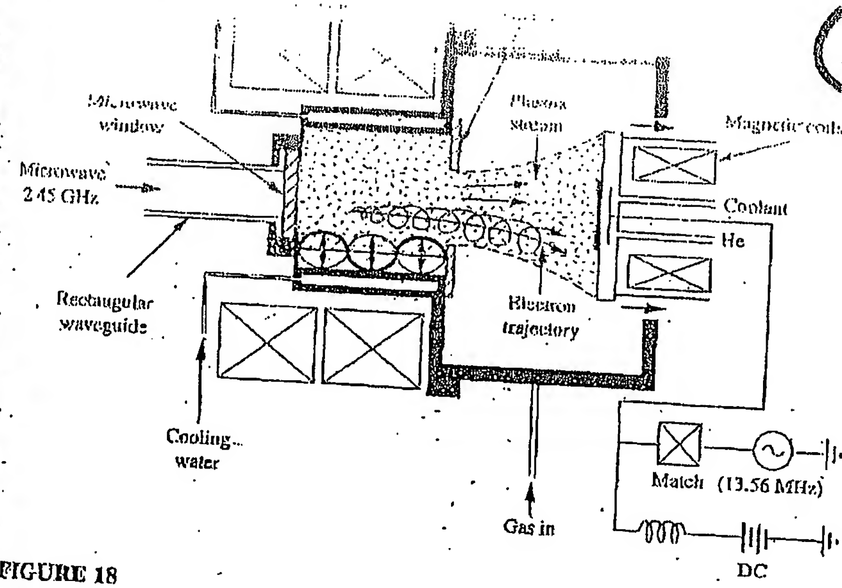

FIGURE 18
Schematic of electron cyclotron resonance etch reactor with a mirror magnetic field around the wafer to confine electron trajectory. (*After Chen et al., Ref. 21.*)

because of the ambipolar diffusion and mirror magnetic field,[21] but a multipole magnetic bucket[22] can be used to improve plasma uniformity. Etch uniformity can also be improved by putting the wafer in an ECR source region surrounded by an optimized magnetic field.[23]

7.4.6 Inductively Coupled and Helicon Wave RF Plasma Etchers

As feature sizes for ULSI continue to decrease, the limits of the conventional rf capacitive-coupled parallel system are being approached. Most ECR plasma reactors are suitable for etching ULSI. However, they are not popular in manufacturing because of their complexity. Other types of high-density plasma sources, such as inductively coupled plasma (ICP) sources or helicon plasma sources, may become the main plasma sources for future ULSI processing. A comparison of recent plasma sources is shown in Table 2.[24] The PMT MORI®source is a helicon wave plasma source. The Lam TCP source is a transformer-coupled plasma source.

An inductively coupled plasma source, shown in Fig. 19, generates high-density, low-pressure plasma that is decoupled from the wafer, and it allows independent control of ion flux and ion energy.[25] Plasma is generated by a flat spiral coil that is separated from the plasma by a dielectric plate on the top of the reactor. The wafer is located several skin depths away from the coil, so it is not affected by the electromagnetic field generated by the coil. There is little plasma density loss because plasma

... available plasma sources*

Plasma source compariso...

	rMT MORI	Lam TCP	Hitachi ECR	Drytech Hol. Anode	Prototech Helical Res.	Lucas Labs Helicon
Source freq. (MHz)	13.56	13.56	2450	13.56	13.56	13.56
Sub. bias freq. (MHz)	13.56	13.56	2/13.56	13.56	13.56	13.56
Source B field (gauss)	50–120	—	800	—	—	50–400
Ion density (cm^3 at wafer)	3×10^{12}	0.5–2×10^{12}	1×10^{11}	1×10^{12}	1.00×10^{12}	3×10^{11}
Ion potential (eV)	20+	20+	20+	20+	20+	20+
Electron temp. (eV)	3.5	3.5–6	4	3–5	4	4
Pressure range (mtorr)	0.5–10	1–25	0.4–10	10–180	0.05–3000	1–10

*No magnetic field at wafer.

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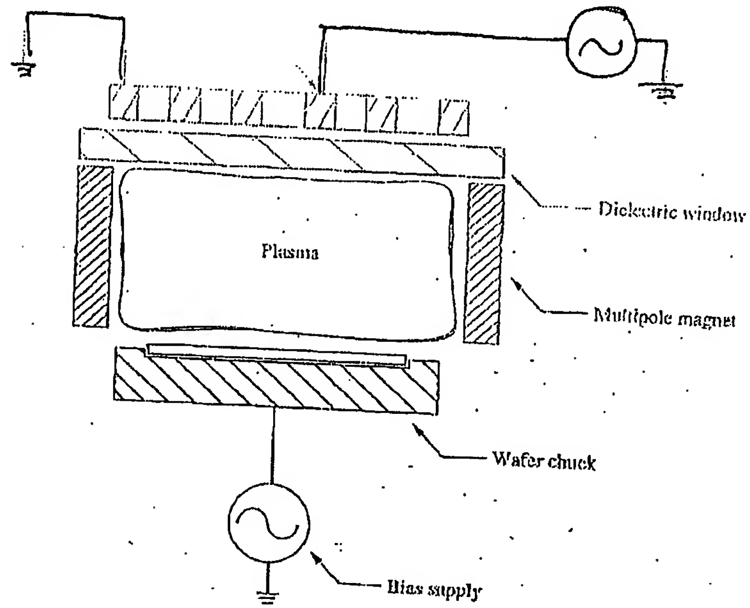

FIGURE 19
Illustration of an inductively coupled plasma reactor. (*After Keller, Forster, and Barnes, Ref. 25.*)

is generated only a few mean free paths away from the wafer surface. Therefore, a high-density plasma and high etch rates are achieved.

A helicon plasma source can also be used to generate a high-density ($> 10^{11}/cm^3$) discharge. A transverse electromagnetic radio-frequency wave (13.56 MHz), excited by a double-loop or single-loop antenna located outside a quartz source tube, is coupled with a steady longitudinal magnetic field B_0 (approximately 100 gauss) generated by a solenoid coil, as shown in Fig. 20.[26] The resonance condition (propagation of a helicon wave) depends on the magnitude of the longitudinal field and the dimension of the reactor. If the wavelength of the helicon wave is the same as the antenna length, the coupling will be resonant. High-density plasma then diffuses into the wafer chamber. In addition, the wafer can be biased separately with a second rf generator.

7.4.7 Clustered Plasma Processing

Microelectronic device wafers are processed in cleanrooms to minimize exposure to ambient particulate contamination. As device dimensions shrink, particulate contamination becomes a more serious problem. To minimize particulate contamination and preserve the integrity of thin film interfaces, clustered plasma tools use a wafer

skimming the surface in the skin layer. Only when F_L is included do the electrons reach the interior with enough energy to ionize. This effect, which requires non-Maxwellian electrons as well as nonlinear forces. can explain why the density peaks at the center even when the skin layer is thin. Because of such non-classical effects, ICPs can be made to produce uniform plasmas even if they do not have antenna elements near the axis.

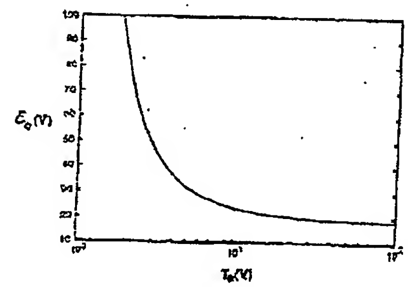

Fig. 22. The E_c curve, a very useful one in discussing energy balance and discharge equilibrium (L & L, p. 81).

4. Ionization energy.

How much RF power does it take to maintain a given plasma density? There are three factors to consider. First, not all the power delivered from the RF amplifier is deposited into the plasma. Some is lost in the matchbox, transmission line, and the antenna itself, heating up these elements. A little may be radiated away as radio waves. The part deposited in the plasma is given by the integral of $\mathbf{J} \cdot \mathbf{E}$ over the plasma volume. If the plasma presents a large *load resistance* and the matching circuit does its job, keeping the reflected power low, more than 90% of the RF power can reach the plasma. Second, there is the loss rate of ion-electron pairs, which we have learned to calculate from diffusion theory. Each time an ion-electron pair recombines on the wall, their kinetic energies are lost. Third, energy is needed to make another pair, in steady state. The threshold energy for ionization is typically 15 eV (15.8 eV for argon). However, it takes much more than 15 eV, on the average, to make one ionization because of inelastic collisions. Most of the time, the fast electrons in the tail of the Maxwellian make excitation collisions with the atoms, exciting them to an upper state so that they emit radiation in spectral lines. Only once in a while will a collision result in an ionization. By summing up all the possible transitions and their probabilities, one finds that it takes more like 50–200 eV to make an ion-electron pair, the excess over 15 eV being lost in radiation. The graph of Fig. 22 by V. Vahedi shows the number of eV spent for each ionization as a function of KT_e.

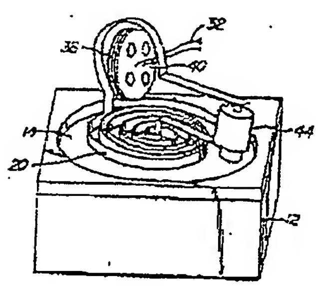

Fig. 23. Drawing of a TCP from the U.S. Patent Office.

5. Transformer Coupled Plasmas (TCPs)

As shown in Fig. 23, a TCP is an ICP with an antenna is shaped into a flat spiral like the heater on an electric stove top. It sits on top of a large quartz plate, which is vacuum sealed to the plasma chamber below containing the chuck and wafer. The processing chamber can also have dipole surface magnetic fields, and the antenna may also have a Faraday shield consisting of a

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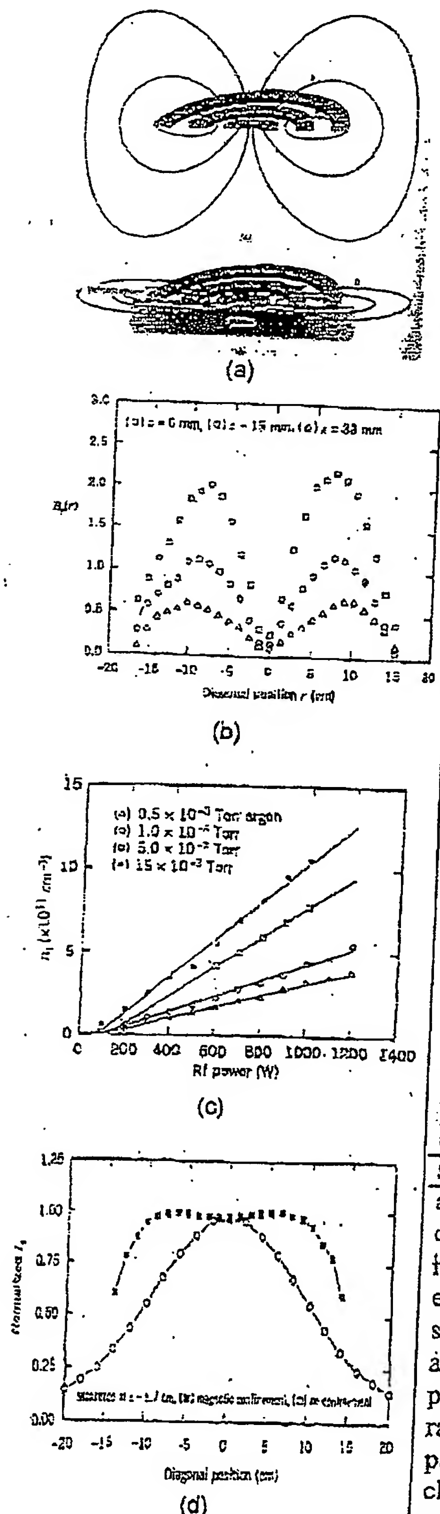

plate with radial slots. According to our previous discussion, the induced electric field in the plasma is in the azimuthal direction, following the antenna current. Electrons are therefore driven in the azimuthal direction to produce the ionization. As in other ICPs, the skin depth is of the order of a few centimeters, so the plasma is generated in a layer just below the quartz plate. Fig. 24a shows the compression of the RF field by the plasma's shielding currents. The plasma then diffuses downwards toward the wafer. In the vicinity of the antenna, its structure is reflected in irregularities of plasma density, but these are smoothed out as the plasma diffuses. There is a tradeoff between large antenna-wafer spacing, which gives better uniformity, and small spacing, which gives higher density. Being one of the first commercially successful ICPs, TCPs have been studied extensively; results of modeling were shown in Fig. 14. Densities of order 10^{12} cm^{-3} can be obtained (Fig. 24c). Magnetic buckets have been found to improve the plasma uniformity. There is dispute about the need for a Faraday shield: though a shield in principle reduces asymmetry due to capacitive coupling, it makes it harder to ignite the discharge. If the antenna is too long or the frequency too high, standing waves may be set up in the antenna, causing an uneven distribution of RF power. The ionization region can be extended further from the antenna by launching a wave—either an ion acoustic wave or an $m = 0$ helicon wave, but such TCPs have not been commercialized. The spiral coil allows the TCP design to be expanded to cover large substrates; in fact, very large TCPs, perhaps using several coils, have been produced for etching flat-panel displays.

TCPs and ICPs have several advantages over RIE reactors. There is no large RF potential in the plasma, so the wafer bias is not constrained to be high. This bias can be set to an arbitrary value with a separate oscillator, so the ion energy is well controlled. The ion energies also are not subject to violent changes during the RF cycle. These devices have higher ionization efficiency, so high ion fluxes can be obtained at low pressures. It is easier to cover a large wafer uniformly. In remote-source or detached-source operation, it is desired to have as little plasma in contact with the wafer as possible; the plasma is used only to produce the necessary chemical radicals. This is not possible with RIE devices. Compared with ECR machines, ICPs are much simpler and cheaper, because they require no magnetic field or microwave power systems.

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TCP™ Design

Transformer Coupled Plasma™ Source Technology

Lam's patented TCP technology is employed in Lam silicon and metal etch systems. Lam's silicon etch systems, such as the 2300™ Versys Star™, are used for all silicon etch applications, such as gate, metal gate, STI, nitride spacer, and recess applications. Specifically, the 2300 Versys Star targets complex, advanced applications to sub—90 nm on 300—mm wafers for current processes and to sub—65 nm for next—generation processes. Applications include:

- All—in—one gate etch (trim, mask open, strip, and gate) in the same chamber
- Gate etch stopping on high—k gate oxides and metal gates
- Shallow trench isolation (STI) with in situ hard mask open

Metal structures, such as 150—nm aluminum interconnect, can be etched with Lam's 200—mm metal etch systems, which employ TCP technology. Geometries at sub—100 nm can be etched on Lam's 2300 Versys metal etch system, where TCP technology has been extended for 300—mm processes. With metal etch, key drivers are productivity and low overall production costs. Lam's metal etch systems incorporate proprietary technologies in their design, such as unique chamber materials and in situ cleans after each wafer is processed, to provide the required high productivity.

How It Works

Source Power

TCP technology efficiently couples RF power into a low—pressure gas to produce a partially ionized plasma (electrically excited ionized gas) at low pressures to etch nanoscale features into silicon and metal films on the wafer surface. The source power is supplied by a simple planar coil located at the top of the etch chamber. A separate power supply delivers bias voltage to the lower electrode (wafer) to provide independent control of ion energy, which influences parameters such as selectivity and CD bias.

Low Pressure

Producing plasma under low pressure is often desirable because there are fewer random collisions among the ionized and neutral species in the plasma. When there are fewer collisions, the ionized and neutral species are more uniformly distributed in the chamber above the wafer, leading to better plasma and etch rate uniformity as well as improved profile control for isolated and dense features.

Damage Control

High—density plasmas at very low pressures are known to cause physical and/or latent device damage. This type of device damage (commonly referred to as "electron shading") is related to the imbalance of electron (negatively charged) and positive ion fluxes at the bottom of high—aspect—ratio features. This imbalance can drive a net electrical current through the device as the features are being etched. A higher plasma density increases the net current and, as a result, increases the potential for device damage.

One of the main features of Lam's TCP technology is the ability to strike plasmas at various powers and pressures. Creating and maintaining the plasma at the proper pressure and density can suppress device damage while achieving the required etch characteristics.

Flexible

Lam's robust TCP source technology allows flexibility for a wide range of power, chemistry, and pressure combinations to produce the desired wafer characteristics. In addition, Lam has introduced technologies to direct gas flow and control wafer temperature that further enable control of the critical dimensions (CD) that determine a chip's usability.

Key Advantages

- Produces a uniform, high—density plasma across the wafer, center to edge, for precise profile control
- Capable of generating a high—density plasma without requiring magnetic enhancements that can cause device damage
- Enables fast and accurate changes in power to perform multiple etch steps in situ, such as gate etch (trim, mask open, strip, and gate) and STI (hard mask open and trench etch)
- Provides the process window flexibility required to etch a wide variety of advanced device structures, such as STI and gate etch stopping on high k gate oxides and metal gates with one hardware configuration

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